The JPL Telerobot Operator Control Station: Part II - Software

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ABSTRACT

The Operator Control Station of the JPL/NASA Telerobot Demonstrator System provides the man-machine interface between the operator and the System. It provides all the hardware and software for accepting human input for the direct and indirect (supervised) manipulation of the robot arms and tools for task execution. Hardware and software are also provided for the display and feedback of information and control data for the operator's consumption and interaction with the task being executed. This paper, Part II, addresses the software design of the OCS.

1.0 INTRODUCTION

The JPL/NASA (Jet Propulsion Laboratory / National Aeronautics and Space Administration) Telerobot Demonstrator System is a research testbed for the development, integration and testing of advanced robot control technologies. The component technologies and system-wide design experiences derived from such a system development and technology demonstration are targeted for use in future space programs, including the NASA's Flight Telerobot Servicer project.

The Operator Control Station (OCS) is a part of this Telerobot Demonstrator System. It contains state-of-the-art hardware, both mechanical and computing, for providing control input to the System. It contains software, in controls as well as human operator interface, for real-time and user-friendly interaction. Video displays for text, graphics and camera images are provided for operator consumption; where appropriate, voice input/output is provided to reduce operator work-load. Data manipulation such as object designation capability is provided for efficient task definition and execution. Access to all Telerobot subsystems is provided for software development and on-line monitoring.

The OCS system design and hardware configuration have been discussed in details in Part I of this paper [ref.1]. This paper, Part II, concentrates on the software design.

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2.0 OCS SOFTWARE REQUIREMENTS

Software required in the OCS includes the processing of OCS input/output data; interface software with other subsystems (in the Telerobot Demonstrator System); system mode switching and supervision; and man-machine interface including object-data-manipulation. Other closely related controls software, including the processing of the force-reflecting-hand-controllers kinematics and dynamics, the processing of the force-torque displays, various other system management functions and supervisory control man-machine interface will not be discussed in here. This is because certain project partitions have allocated these functions in other subsystems in the overall system architecture design. Specific OCS software requirements are to provide:

1. Command interpreter to process operator generated commands via the keyboard, mouse, and voice; hence to parse, translate, and generate inter- and intra-OCS commands;
2. Message processor for translating, generating, and displaying messages on OCS monitor; for messages initiated from within or outside OCS;
3. RS-232 controllers for graphics overlay/mixer controllers, voice display controller, and video switch controller;
4. Gateway computer interface via an ethernet network;
5. NIP (a custom Network Interface Package [ref.2]) gateway interface software for processing NIP transactions from other subsystems;
6. Object designation/definition software to create wire-frame models, overlay on camera images, manipulate using mouse cursors, perform best-fit, update and augment data bases; and to interface with the Planning and Reasoning Subsystem for models and data;
7. Interface software between the primary workstation and secondary workstation;
8. Terminal emulation to all subsystems via multiple windows on the OCS monitor;
9. Pull-down and pull-right menus for system and subsystem commands;
10. Continuous speech voice recognition with error correcting and custom vocabulary grouping schemes for direct voice input; multi-voice (gender/person) speech synthesis for message output;
11. Graphics generation and overlay software for object designation/verification.

Other pertinent requirements on the OCS will not be discussed in this paper, because of their allocation to other susbystems in the present Telerobot Demonstrator System design. Nonetheless, these other requirements are enumerated in [ref.3].

Performance requirements on the OCS software include:
i. Both the primary and secondary workstations shall have identical software and input-output process from the terminal, keyboard and mouse; (by design and because of hardware limitation, the secondary workstation cannot input FRHC teleoperation controls and does not have stereo vision displays);
ii. Both the primary and secondary workstations shall share common software for executing and interfacing commands between the command interpreter/message display processes and the rest of the OCS internal/external software; this common software shall reside in the primary workstation;

iii. Inputs from both workstations shall not be prioritized, and shall be processed sequentially by the time order that the inputs arrive;

iv. Flexibility shall be maintained in the overall structure, grouping, and individual specification of the set of commands; the entire set shall be kept in a separate command definition file, which can be modified and edited independent of the compilation of the main OCS software;

v. Similar flexibility shall be maintained in the set of messages; the entire set shall be kept in a separate message definition file, which can be edited independently;

vi. The set of vocabulary words, grouping and grammar of the speech input sentences shall be designed to achieve 98%+ Type I recognition accuarcy and 95%+ Type II false alarm rejection accuracy; with the use of interrogation and operator interaction, the overall accuracy achievable shall be improved to 99%+;

vii. The accuracy of the object designation process shall be within one pixel RMS (root mean square) averaged over the vertices of the object; (absolute accuracy is not specified, because it is a factor of the distance of the object from the cameras and depends on camera model accuracies);

viii. The primary OCS workstation mouse shall be shared between the normal OCS command process and the object designation process which utilizes the mouse for graphic entries; (this property eliminates the proliferation of mouse(s); each graphic overlay machine for the object designation process requires one mouse);

ix. During the object designation process, OCS commands shall continue to be receivable through voice input; keyboard and mouse inputs can be toggled between the designation and command processes, using a switch on the mouse;

x. Menus and direct keyboard inputs shall be designed to good human enginnering standards.

3.0 OCS SOFTWARE DESIGN

The OCS software consists of ten processes distributed among a Sun-3/160, which serves as the primary workstation, a Sun-3/60, the secondary workstation, and a DEC μVAX, which is the communications gateway computer for interface among the other subsystems. These processes provide the following OCS functions:

   o Command Interpreter
   o Message Processing and Display
   o Ethernet Interface, Sun/microVAX
   o External Subsystem Interface
   o Video Switch Operation and Control
   o Wire Frame Object Designation

The dual workstation design allows OCS commands to be issued from either the primary or the secondary workstation, and provides for messages generated on either workstation, or by external subsystems, to be displayed on both workstation monitors. Voice input and audio output capabilities have been included to aid the operator. A continuous speech recognizer is provided to accept operator voice commands, which are routed to the OCS Command Interpreter. A speech synthesizer is provided to

acknowledge voice commands, as well as annunciate important messages that may occur when the operator's attention is directed away from the workstation display. Multiple voices are utilized to assist the operator in message recognition.

The processes which constitute the OCS program set are illustrated in Figure 1. The SunView Notifier is shown with the processes that provide direct window interface to the users by either accepting operator input or displaying messages. Inter-process communication methods used by the OCS software, include Remote Procedure Calls, Unix Sockets, Pipes, and DECnet. Figure 1 also shows the Ethernet dividing the primary from the secondary workstation, and separating the OCS software which resides on the Sun workstations from the µVAX gateway computer and external subsystems.

The OCS Command Interpreter resides on both the primary and the secondary workstation, and receives operator commands from the speech recognizer, as well as the standard Sun keyboard and mouse. Interpreted command data is sent to other OCS functions in the form of command interface records by means of Sun's Remote Procedure Call (RPC) and eXternal Data Representation (XDR) facilities, which provide for inter-process communication regardless of the host in which the serving process resides.

The OCS command interface, in addition to allowing direct keyboard and voice commands, provides a customizable multi-level menu interface that is controlled by the Sun three-button mouse. Menu display is activated by clicking a mouse button, or selecting an icon, and command selections are made by positioning the mouse cursor over the desired option. Many menu items contain a "pullright" capability, which, when selected by the mouse cursor, causes the next level of menu options to be displayed to the right of the current selection. The operator may specify, during OCS activation, the degree to which previous menu selections influence subsequent menu display.

The Message Processor accepts message definition records, which contain message ID's and message attributes, from all OCS processes, and generates messages for display on the Sun monitors and for annunciation by means of the DECtalk speech synthesizer. Messages targeted for monitor display are routed to the message display software on both the primary and the secondary workstations so that all messages are displayed on each workstation.

The Ethernet Interface function of the OCS provides the Sun interface with the µVAX gateway computer. This function accepts command interface records from processes on either Sun workstation, extracts pertinent data for interface with external subsystems, and sends host-to-gateway records over the Ethernet to the External Subsystem Interface function on the µVAX via DECnet. The Ethernet Interface function also accepts gateway-to-host records over the Ethernet from the External Subsystem Interface function, extracts pertinent data, and distributes the data to the appropriate OCS process by means of (1) command interface records using RPC facilities, (2) message definition records, also using RPC, and (3) data written on a Unix socket connected with the Video Switch Operation function.

The External Subsystem Interface function resides on the μVAX as the communication interface between the OCS software that executes on the Sun workstations and the external subsystems. This inter-subsystem communication is done using Network Service Transactions (NST's) which are controlled by the NIP. The External Subsystem Interface function receives host-to-gateway records over the Ethernet from the primary Sun host via DECnet services, and uses the data to initiate or respond to NST's with other TDS subsystems. In addition, NST records that originate from external subsystems are received and validated by this function. Validated data is extracted from the NIP NST's, formatted into gateway-to-host records, and sent via DECnet to the Ethernet Interface function on the Sun primary workstation.

The Video Switch Operation and Control function resides on the primary Sun workstation and provides the software interface to the OCS video switch hardware. The Video Switch Operation function interfaces with the external S&P Subsystem, by means of the OCS Ethernet Interface and External Subsystem Interface functions, to request remote switching of the cameras and frame buffers to operator selected video channels, and to receive the remote video switch status.

The Wire Frame Object Designator function resides on the primary Sun workstation and provides the capability for objects whose position and orientation are unknown or invalid to be designated and subsequently used in the System database. The designation is performed by means of wire frame diagrams, based on object and camera model data, being overlayed on actual video images, manipulated in terms of translation and rotation, and fit with the video image by means of vertex designation and a least-squares fit algorithm. The Wire Frame Object Designator function receives object and camera model data from the external TPR Subsystem, by means of the OCS Ethernet Interface and External Subsystem Interface functions, and returns updated camera model data after an object has been designated. In addition, object designation commands from the operator are received in command interface records sent by the OCS Command Interpreter process.

An extensive user interface for the Teleoperation Subsystem is provided to facilitate both operator input and status recognition for the robot manipulators and the force-reflecting hand controllers, their states, joint limiting situations, operating modes, etc. Numerous icons are provided for the selection of the various teleoperation command and status windows. A direct communication link with the Teleoperation computer is provided, and voice teleoperation commands received by the Command Interpreter function are routed to the Teleoperation Subsystem by this link.

The OCS software has been designed to operate within the SunView Windows user interface environment. The OCS window layout can be customized by the operator to a large degree, including the size and position of the windows, the default character font, icon positioning, the look of menus, etc. The windows may be moved about the Sun display, resized, or closed into icons, and many window option defaults may be selected according to the operator's desires. Easily identifiable iconic representations for each of the OCS windows have been provided, and the mouse cursor image is modified to indicate the active window in order to give additional visual cues to the operator.

Integrating the OCS operator interface with the SunView environment also provides a flexible capability for the operator to perform terminal emulation with all the external subsystems. Terminal emulation windows may be opened when direct interface with another subsystem is required, and subsequently destroyed, or left active in an iconic state for future use. Multiple terminal emulation windows may be active simultaneously, in addition to the OCS processes.

This implementation approach allows the operator a great deal of flexibility in the user-interface with the OCS, and provides a familiar look and feel for a user experienced with the Sun window environment.

The following three subsections further describe the Command Interpreter process, the Message Definition and Display process, the Ethernet and External Subsystem Interface process. Explicit discussion on the Video Switch Operation and Control is avoided because of the simplicity of the process. Discussion on the Object Designation process has been given in [ref.1,4].

3.1 Command Interpreter

Table 1 is a condensed table of the OCS command set. The OCS Command Interpreter function provides a flexible, table driven capability for command definition, recognition, interpretation, and inter-process distribution. Valid commands for direct keyboard entry, voice input, and menu selections, as well as command and command-qualifier relationships, are defined in a standard text file, the command definition file, and can be modified by the user to change the command interpretation and processing traits of the OCS without modification of the software.

The command definition file completely defines the command processing characteristics of the OCS. Specific keyboard and voice commands are defined, as are command groupings, menu content, and the text of menu selections. Command translation data is defined for process specific or device specific information to be supplied in conjunction with a particular command. The command destination--that is, the target program that will process the command, is also specified for each command, as is any required NST data associated with the command, such as the destination subsystem, record type and identification, and subsystem interchange protocol. Each command may be specified as requiring confirmation before being processed, providing a measure of protection from inadvertent command selection.

The purpose of the command definition file and the Command Interpreter flexibility is to allow the OCS and Telerobot Demonstrator System functionality to evolve, without the necessity of redesigning or modifying the command processing function. Additional processes which may be added to the OCS at a later date, will be able to use the same user interface, yielding consistency as the System capabilities evolve. Commands may be grouped into menus, and the text of the menus may be modified after the user has gained experience with the system and becomes aware of changing needs. In fact, multiple command definition files may be defined to allow

each operator to customize his or her interface with the OCS according to individual preference or the tasks to be performed.

The operator interface to the Command Interpreter function makes use of the SunView Window services, and the SunView Notifier, which directs processing control based on user input by direct keyboard entry, mouse-based menu selections, or voice input. Voice input from the speech recognizer is directed to the Command Interpreter function, regardless of which SunView window is active.

Once the Command Interpreter has received a command from the operator, the command is looked up in the command definition table, which is built at initialization from the command definition file. Commands and their associated qualifiers are validated, and command confirmation is requested when so indicated. Command validation or cancellation may also be performed by use of keyboard or voice input, or by clicking the mouse buttons. For valid, confirmed commands, the data in the command definition table is used to build a command interface record, which is then sent to the specified destination for processing.

The Sun RPC (Remote Procedure Call) services are used for inter-process communication between the Command Interpreter, which resides on both the primary and the secondary workstation, and the other OCS functions, which operate on the primary workstation. Together with the XDR (eXternal Data Representation) services provided by Sun, which organize data bytes in a machine independent format, RPC allows an inter-process communication client process to communicate with a server process on any valid host computer. These facilities enable the Command Interpreter to execute on either workstation without requiring special-purpose software for network interface from the secondary workstation's Command Interpreter to OCS functions that reside on the primary workstation.

3.2 Message Processing and Display

Table 2 is a condensed table of the OCS message set. The OCS Message Processing and Display function provides a centralized, table driven interface to the OCS message windows on the Sun workstations, and the voice output device.

The Message Processing server process for RPC from other OCS functions resides on the primary workstation as the target of all Message Definition Records. This process builds the message text based on the incoming data and the specification in the Message Definition Table, and routes the message text to the DECtalk speech synthesizer, and the Message Display software residing on both the primary and the secondary workstations. Audio output may be enabled or disabled by normal OCS commands, and the gender of the message voice is selected based on the attributes specified in the Message Definition Table.

A standard ASCII format Message Definition File is used for the specification of message ID's, attributes, and text, which are processed into the Message Definition Table during initialization. The message attribute specification allows a message to be defined as a normal or critical text message, and/or a male voice, or female voice

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message. The use of the Message Definition File allows messages to be added or changed, or the characteristics of a message to be revised based on evolving system needs, without requiring redesign or modification of the existing OCS software.

A separate message window is utilized to inform the operator of critical messages. The display of a critical message is accompanied by an audible beep, a visual flashing of the critical message window, and if the message window had been closed into an icon or hidden behind another window, it is automatically opened and exposed to operator view. Both critical and normal messages are displayed in the normal message window, which provides a context for any critical messages that may be generated during an operational session.

All valid commands are acknowledged by messages in the normal message window, and all messages are displayed at both the primary and the secondary workstation with an indication of the workstation that generated the message. These features allow each OCS workstation operator to be aware of the actions of the other operator, as well as any system or error messages that arise, and provides a history of commands and how they were generated.

The capability to store OCS messages from both the critical and normal message windows to a user specified file is provided, along with the option for the operator to clear each message window individually - to eliminate outdated critical messages, for example. The workstation mouse is used to activate a menu and select the desired option.

The OCS message windows may be closed in icons or positioned on the workstation display independently from the other OCS windows, such as the command window. This flexibility allows the OCS message display to be rearranged according to individual operator preferences or processing needs.

3.3   Ethernet and External Subsystem Interface

The Ethernet Interface and External Subsystem Interface functions of the OCS work together to provide a centralized interface between the Sun workstations and the μVAX gateway computer, and between OCS and the external subsystems.

The Ethernet Interface function consists of two separate processes, one for sending host-to-gateway records from the Sun to the μVAX, and the other for receiving gateway-to-host records from the μVAX. Upon initialization of the Ethernet Interface function on the Sun primary workstation, DECnet services are used to activate the External Subsystem Interface function, which executes on the communications gateway μVAX, and establish a communication link over the Ethernet between the two functions.

The External Subsystem Interface function receives host-to-gateway records from the Sun, extracts the data and builds the NIP/NST records to be sent to the other subsystems, then interfaces with the NIP to ship the NST records. All interface with the NIP software is performed in this function, which also receives NIP/NST records

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directed to the OCS from the other subsystems. Data is extracted from the incoming NST records, packaged into gateway-to-host records, and sent to the Ethernet Interface function over the Ethernet.

The Ethernet Interface function receives the gateway-to-host records sent from the External Subsystem Interface function, and examines the record content to determine which OCS process should receive the data. Message data is sent by means of RPC's to the Message Processing function. Other data is used to generate Command Interface Records, which are also sent via RPC to the destination process. Video switch status from the S&P subsystem is sent over a connected Unix socket to the Video Switch Operations and Control function, which is waiting for the status in order to complete a video switch setting operation, while object and camera model data sent by the TPR subsystem is distributed to the Wire Frame Object Designation function using an RPC interface.

Current design contains the following NST's. (OCS-to-SE): (i) Comm_Link_Test; (ii) SE_Start-Up, (iii) SE_Shut_Down, (iv) SE_Halt. (OCS-to-S&P): (v) Select_Video_Sources, (vi) Read_Video_Sources. (OCS-to-TPR): (vii) Vision_Arm_Control, (viii) Object_Designate. (OCS-to-all): (ix) Message.

4.0 SUMMARY

As mentioned in Part I of this paper, the present OCS design is an evolutionary design which will evolve and change as the telerobot technology matures, both in system design and in component design. The present design is believed to have the necessary 'hooks and scars' for future system expansion, both in software and in hardware. Despite its flexibility, certain architectural features are recognized to be suboptimal because of project constraints. These constraints have been discussed in Part I of this paper.

After complete integration in the Telerobot Demonstrator System testbed laboratory in Summer, 1989, the OCS will serve as the focal point of the Demonstrator System. Real hands-on operational flow analysis and workload analysis will be conducted, so as to evaluate the effectiveness of the OCS design, and of the integrated telerobot system. More research and development items, improvements on point-designs, alterations of physical layout, addition of vocabulary, etc. will undoubtedly surface when more experience is gained from OCS and telerobot experiments. As more powerful computers become available, and as the understanding of a telerobot system matures, the state-of-the-art OCS technology will evolve.

5.0   Acknowledgements

6.0   References

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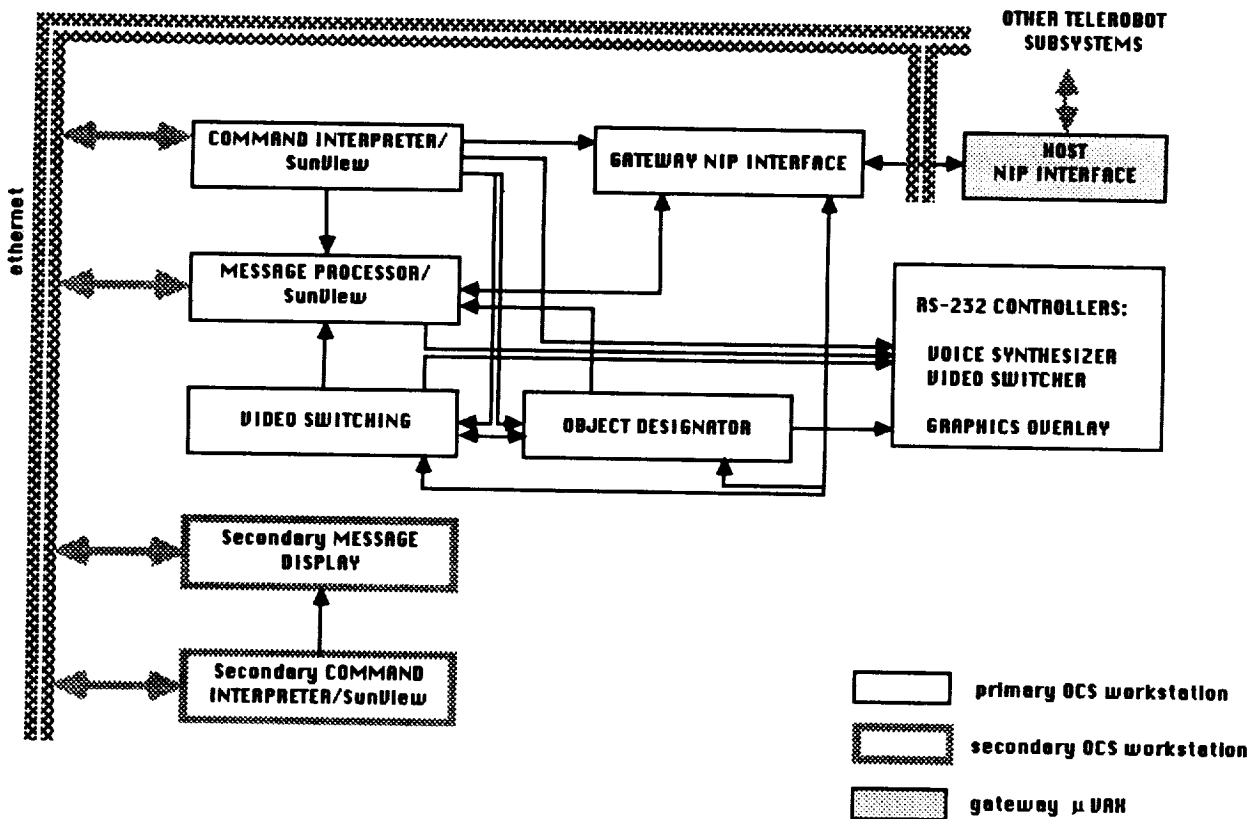
Figure 1.   OCS SOFTWARE FUNCTIONAL BLOCK DIAGRAM

Table 1.   OCS Command Set (condensed)   'KEYBOARD' & "Voice"

HOST CONTROL:	'Quit OCS' ("Quit OCS"); 'Audio' ("Enable Audio"); 'Noaudio'; 'Audio Ack'; 'Noaudio Ack'; 'Vsdflt'; 'Swst'
VIDEO SWITCH CONTROL:	'C1' ("CameraOne"); 'C2'; . . . ; 'C5'
	'B1' ("BufferOne"); 'B2'; . . . ; 'B4'
	'CH1' ("ChannelOne); 'CH2'; . . . ; 'CH5'
	'RFT' ("RightForceTorque"); 'LFT'
	'STE' ("StereoCameras); 'OH' ("OverheadCameras")
	'RW' ("RightWing"); 'LW'
	'WF' ("WireFrame"); 'DROP' ("Drop")
	'SWST' 'parameters' ("SwitchStatus" "parameters")
OBJECT DESIGNATION:	'conj'; 'top'; 'bot'; 'left'; 'right'; 'rear'; 'rotate'; 'manip'; 'fit';'undo'; 'erase'; 'done'; 'cancel'; 'next', 'color'; 'wf_cont'; 'select'; 'clear'
VISION ARM CONTROL:	'va'; 'vastop'; 'hold'; 'a' ("moveagain"), 'back'; 'goback', 'wm' ("WorldMode") 'tm ("ToolMode"); 'P1' ("Movetoposition1") 'P2'; ...; 'f' ; 'b'; 'r'; 'l'; 'u'; 'd'; 'pr'; 'pl'; 'tu'; 'td'; 'mm' ("move-more"); 'sa'; 'lm'; 'ls'; 'bm'; 'ss';
TELEOP CONTROL:	'teleop'; 'telestop'; 'idx'; 'lidx'; 'ridx'; 'pos'; 'lpos'; 'rpos'; 'rat'; 'lrat'; 'rrat'; 'jnt'; 'ljnt'; 'rjnt'; 'crnt'; 'lcrnt'; 'rcrnt'; 'tst'; 'ltst'; 'rtst'; 'one'; 'two'; ...
SYSTEM EXEC COMMANDS:	'systart'; 'shutdown'; 'halt';

Table 2.   OCS Message Set (condensed)   'Message window' & "Voice"

MESSAGE DEFINITION FILE LISTS ALL MESSAGES BY: MESSAGE ID; ATTRIBUTE; AND TEXT.
ATTRIBUTES ARE: (1) normal; (2) critical; (4) male voice; (8) female voice.

INTERNAL MESSAGES:	'quitting'; 'initializing'; 'input error on %s'; 'command %s is not recognized' ("%s is not recognized"); 'error - getting OCS video switch routing status %s'; ....
VIDEO SWITCH warning:	'unknown video switch name %s' ("named video switch not known"); 'invalid video switch command'; ...
WIREFRAME OB DES errors:	'bad camera # received' ("requested selection not done"); ...
WIREFRAME OB DES warnings:	'unknown obj des command %s' ("illegal command"); 'cannot fit, no points saved' ("no points saved"); .....
WIREFRAME OB DES status:	'object designator active' ("object designator active"); 'mouse being used for object designation'; .....
VDT MONITOR warnings:	"no point to erase!", "showing different camera view!"; ....
VDT MONITOR status:	"%s points saved!"; "object rotated to show top view"; "undo done!"; "object partially out of camera view"; ...
SUBSYSTEM messages:	'MCM requires attention' ("the MCM requires attention"); ...; 'va limit stop joint 1'; ...;'SE status: warning (1)';....